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Research Article

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Temperature dependence on series resistance of a silicon solar cell under polychromatic illumination

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Abstract The series resistance is an important electrical parameter of the solar cell which can be determined from the Photocurrent - Photovoltage characteristic knowing the recombination velocity of the minority carriers at the junction limiting the open circuit. The temperature application makes it possible to study its impact on electrical parameters especially the series resistance. Thus, expression of the minority charge carrier density is determined from the continuity equation which allows us to access photocurrent and photovoltage. From the Photocurrent - Photovoltage characteristic, the series resistance is determined and then studied as temperature dependent. The Junction surface recombination Velocity of Minority Charge Carriers at the junction limiting the open circuit (Sfoc), dependent on the temperature applied, is obtained from the photovoltage and the open circuit voltage. From this recombination velocity, different values of the series resistance for given temperatures are determined

Keywords Silicon Solar Cell – Series Resistance – Open circuit voltage – Junction Recombination velocity – temperature

Introduction

The series resistance (Rs) materializes all imperfections due to contact of the front face and the rear face, contacts between metal and semiconductor and the resistivity of the semiconductor material [1-3]. In static regime [4-6] as in dynamic frequency regime [7-9], the series resistance can be studied. The application of the temperature allows to study its effect on the series resistance of the silicon solar cell under polychromatic illumination and in static regime. The determination of minority charge carriers density from the continuity equation has made it possible to obtain the photocurrent and the photovoltage. From the Photocurrent - Photovoltage characteristic and of the recombination velocity of the minority charge carriers at the junction limiting the open circuit, the series resistance is determined and then studied as a function of the temperature applied.

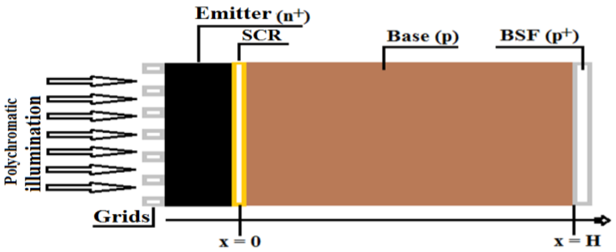

Figure 1: Silicon solar cell n+pp+ type

Theory

In this study we consider a type of solar cell n^+-p-p^+ [10] under polychromatic illumination. The structure of this solar cell is shown in Figure 1.

When the solar cell is illuminated by polychromatic light various phenomena such as the creation of electron-hole pairs, the diffusion of the minority charge carriers in the base as well as the recombination can occur. The whole of these phenomena is governed by continuity equation which is relative to the density of excess minority carriers in the base. It is represented by equation 1:

$$\frac{\partial\delta(x)}{\partial x^2}-\frac{\delta(x)}{L(T)^2}=-\frac{G(x)}{D(T)} \qquad (1)$$

In this equation, D (T) represents the diffusion coefficient which is a function of temperature according to equation (2):

$$D(T)=\mu(T)\frac{k_b}{q}T \qquad (2)$$

$\mu(T)$characterizes the mobility of electrons [11,12] and is a function of temperature, its expression is given by:

$$\mu(T)=1,43.10^9 T^{-2,42} cm^2 V^{-1} s^{-1} \qquad (3)$$

k_b is the Boltzmann constant, q the elementary charge of the electron and T the temperature.

L(T) represents the diffusion length which depends on the diffusion coefficient according to the relationship:

$$\left(L(T)\right)^2=\tau D(T) \qquad (4)$$

τ is the lifetime of the photogenerated charge carriers in the base

G(x) represents the generation rate of the minority carriers which depends on the depth in the base according to relation [13]:

$$G(x)=\sum_{i=1}^{3} a_i e^{-b_i x} \qquad (5)$$

The coefficients ai and bi are obtained from the tabulated values of the radiation under A.M1.5 [14]. These coefficients are given by:

$a_1=6,13.10^{20}$ cm^{-3}/s; $a_2=0,54.10^{20} cm^{-3}/s$; $a_3=0,0991.10^{20} cm^{-3}/s$; $b_1=6630 cm^{-1}$; $b_2=1000 cm^{-1}$;

δ(x) represents the density of minority charge carriers in the base, its expression is given by the resolution of equation (1):

$$\delta(x,\mathrm{T})=A\cosh\left(\frac{x}{L(T)}\right)+B\sinh\left(\frac{x}{L(T)}\right)+\sum_{i=1}^{3}\frac{a_i(L(T))^2}{D(T)\left[(L(T))^2(b_i)^2-1\right]}e^{-b_i x} \qquad (6)$$

The expressions of A and B are determined from the boundary conditions [14,15]:

- at the junction*(x=0)*

$$\left.\frac{\partial\delta(x,T)}{\partial x}\right|_{x=0}=\frac{S_f}{D(T)}\delta(x,T)\Big|_{x=0} \qquad (7)$$

- at the back surface (*x=H*):

$$\left.\frac{\partial\delta(x,T)}{\partial x}\right|_{x=H}=-\frac{S_b}{D(T)}\delta(x,T)\Big|_{x=H} \qquad (8)$$

S_f represents the recombination velocity of the minority charge carriers at the junction. It characterizes the operating point of the solar cell but also the minority carrier flux at the junction [15,16]. Sb is the recombination velocity of the minority charge carriers at the back surface [16]. The expression of the density of the minority carriers makes it possible to access the photocurrent and the photovoltage according to the equations:

$$J_{ph}(S_f,T)=qD(T)\left.\frac{\partial\delta(S_f,T)}{\partial x}\right|_{x=0} \qquad (9)$$

$$V_{ph}\left(S_f,T\right)=V_T\ln\left[\frac{N_b}{\left(n_i^2(T)\right)}\delta\left(0,S_f,T\right)+1\right] \qquad (10)$$

Jph represents the photocurrent density, Vph the photovoltage and N_b the doping rate.

$n_i(T)$ is the intrinsic density of the minority carriers, its depends on the temperature according to the relation [17] :

$$n_i=C.T^{\frac{3}{2}}\exp\left(-\frac{E_g}{2.k_b.T}\right) \qquad (11)$$

With C a constant equal to $3.87.10^{16}$ cm^{-3} $K^{-3/2}$ and Eg the gap energy. This energy is the difference between the energy of the conduction band E_c and that of the valence band E_v. It is equal to $1.12x1.6x10^{-19}$ J for the silicon.

V_T represents the thermal voltage given by:

$$V_T=\frac{k_b}{q}T \qquad (12)$$

Results and Discussions

Equations (9) and (10) yielded the following profiles:

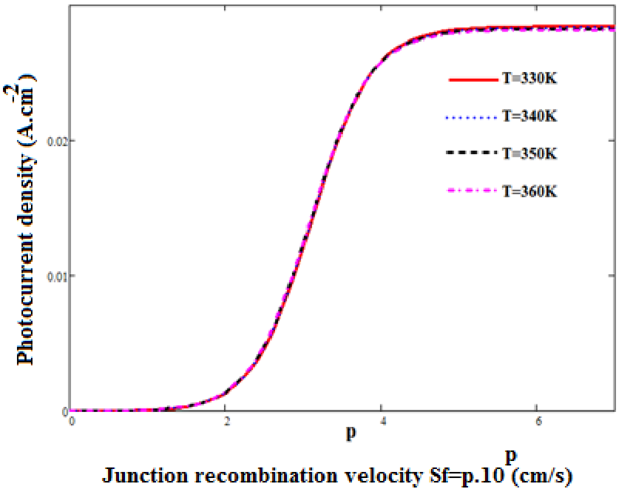

Figure 2: Photocurrent Density as a function of the recombination velocity of the minority charge carriers at the junction for different values of the temperature

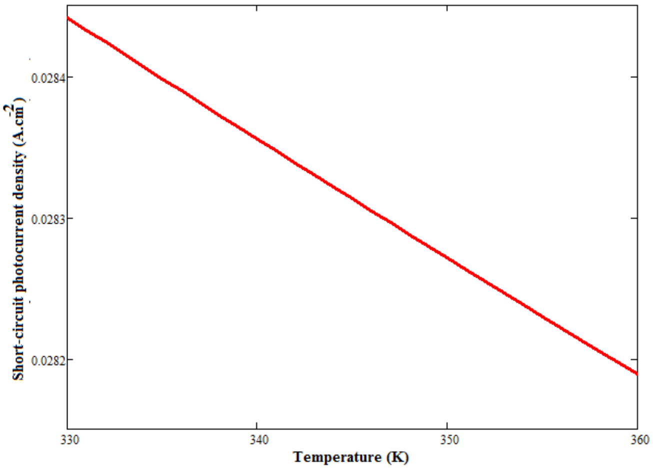

Figure 3: Short-circuit photocurrent density as a function of temperature

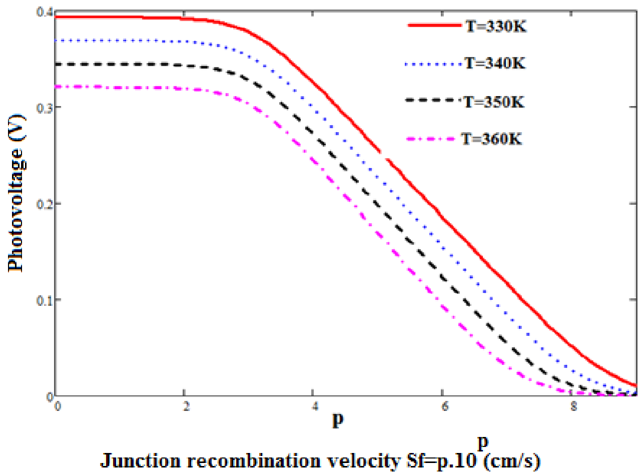

Figure 4: Photovoltage as a function of the recombination velocity of the minority charge carriers at the junction for different temperature values

Figure 2 shows a weak photocurrent in the vicinity of the open circuit (at the low Sf values): The minority carriers are blocked at the junction because they lack energy to cross the potential barrier located at the junction. When Sf increases, the minority charge carriers cross the junction and the photocurrent increases to reach a maximum value at the large Sf values: This is the short-circuit current. We also observe a decrease in the short-circuit current when the temperature increases with very low sensitivity. This observation is confirmed by figure 3. Indeed, at the large values of Sf, the flux of the minority charge carriers at the junction is maximal, so there remains a small amount of the minority charge carriers that can be undergo by the temperature effect. Everything happens as if the increase of Sf tends to inhibit the process umklapp [18-20], that is to say a decrease in the resistivity of the material. On the other hand, at the low values of Sf (in the vicinity of the short-circuit), the minority charge carriers are blocked at the junction leading to a maximum photovoltage: this is the open circuit voltage (figure 4). It decreases when Sf increases to cancel out in the vicinity of the short circuit. Indeed, when Sf increases the amount of stored minority charge carriers decreases which results in a decrease of photovoltage. We also observe that increasing the temperature decreases the open circuit voltage with a sharper sensitivity: Here we have the process umklapp [18-20] which results in an increase in the resistivity of the material. The observations described above are confirmed in the Photocurrent - photovoltage characteristic. It is represented by figure 5.

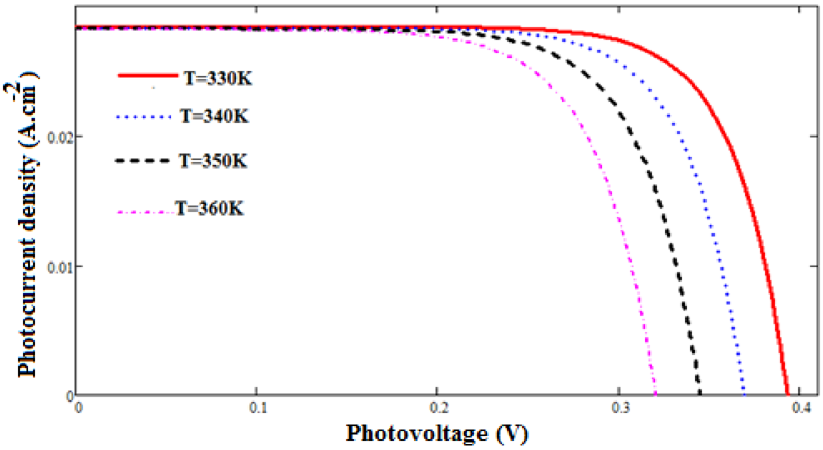

Figure 5: Photocurrent - Photovoltage characteristic for different temperature values

Study of the series resistance

The series resistance (Rs) materializes all imperfections due to contact of the front face and the rear face, contacts between metal and semiconductor and the resistivity of the semiconductor material [21-22]. For the determination of the séries resistance expression, we consider the neighborhood of the open circuit of the solar cell and in these operating conditions an equivalent circuit of the solar cell is presented by figure 6 [23-27].

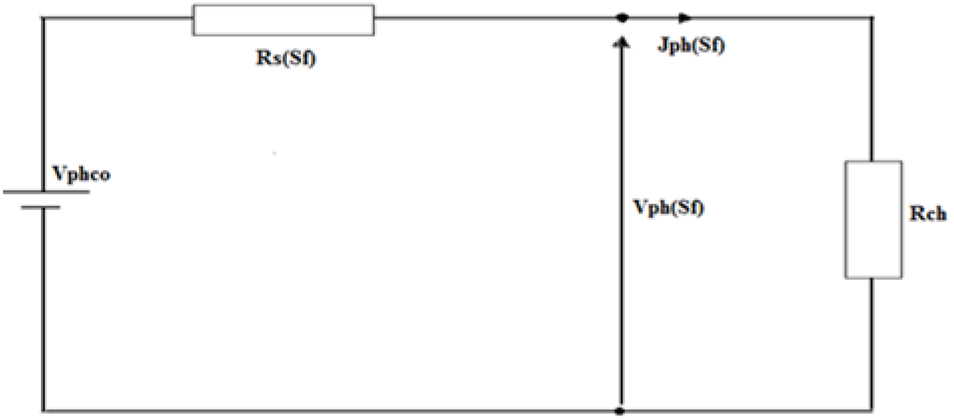

Figure 6: Equivalent electric circuit of the solar cell operating in open circuit

Vphcois the open circuit photovoltageRs (Sf) the series resistance and Rch the resistance of the external load. Jph (Sf) and Vph (Sf) represent respectively the photocurrent density and the photovoltage as a function of Sf.Using this circuit equivalent (figure 6), the series resistance can be expressed

$$R_s(S_f,T)=\frac{V_{phco}(T)-V_{ph}(S_f,T)}{J_{ph}(S_f,T)} \quad (13)$$

From expression 13, we represent in figure 7, the profile of the series resistance as a function of the recombination velocity of the minority charge carriers at the junction for different values of the temperature:

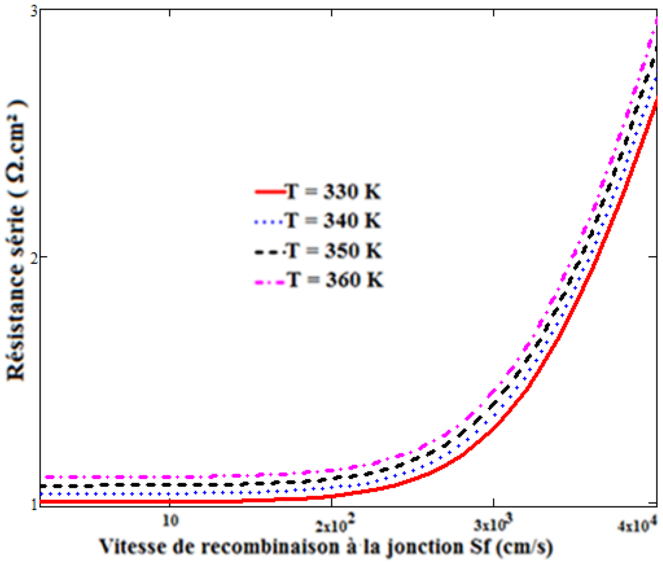

Figure 7: Series resistance a function of the recombination rate at the junction for different temperature values

Figure 7 shows an increase in the series resistance with the recombination velocity of the minority carriers at the junction. Indeed, when Sf increases, the flux of minority load carriers at the junction increases. This reduction of the minority charge carriers in the base of the solar cell leads to a reduction of the dynamic conductivity and consequently causes an increase in the resistivity of the material and therefore of the series resistance. We also note an increase in series resistance with temperature. Indeed, the temperature causes an increase in the resistivity of the silicon material with the umklapp process [18-20], which, in high temperature, causes the reduction of the mobility of the minority charge carriers and consequently an increase in the series resistance.

Determination of the series resistance from the recombination velocity of the minority charge carriers limiting the open circuit (Sfoc)

The expression of Sfoc is obtained from the resolution of Equation 14 [28, 29]:

$$Vph(S_f, T) - Vphoc(T) = 0 \tag{14}$$

Thus, we obtain

$$Sfoc = \frac{E(T) + L(T).\sum_{i=1}^{3} K(T).B_3(T) + L(T).D(T).A_4(T).\sum_{i=1}^{3} K(T).b_i}{E_1(T) - E_2(T) - L(T).A_4(T).\sum_{i=1}^{3} K(T)} \tag{15}$$

With :

$$K(T) = \frac{a_i(T)\left(L(T)\right)^2}{D(T)\left[1-\left(L(T)b_i\right)^2\right]}$$

$$A_4(T) = L(\mathrm{T})\mathrm{S}_b \sinh\left(\frac{H}{L(T)}\right) + D(T)\cosh\left(\frac{H}{L(T)}\right)$$

$$E(T) = A_3(T)D(T)L(T)S_b \cosh\left(\frac{H}{L(\mathrm{T})}\right) + A_3(T)\left(D(T)\right)^2 \sinh\left(\frac{H}{L(\mathrm{T})}\right)$$

$$E_1(T) = -A_3(T)\left(L(T)\right)^2 \sinh\left(\frac{H}{L(\mathrm{T})}\right)$$

$$E_2(T) = A_3(T)L(T)A_4(T)\sinh\left(\frac{H}{L(\mathrm{T})}\right)$$

$$A_3(T) = \frac{\left[n_i(T)\right]^2}{N_b}\left[e^{\left(\frac{V_1co(\mathrm{T})}{V(T)}\right)} - 1\right] - \sum_{i=1}^{3} K(T)$$

Referring to figure 7, the values of the temperature have allowed, after their introduction in equation 15, to obtain the values of Sfoc. These latter, projected at the level of the curves of figure 7, have made it possible to determine the series resistance for different temperature values. The results are recorded in table 1.

Table 1: Sfoc and Rs values for different temperatures

T(K)	Sfoc(cm/s)	Rs(Ω.cm^2)
330	8,7.10^3	1,6
340	8,4.10^3	1,7
350	8,2.10^3	1,8
360	8,0.10^3	1,8

Table 1 shows that the temperature increases the recombination velocity of the minority charge carriers at the junction limiting the open circuit. Thus, more the temperature increases, more the resistance of the material increases (with the umklapp process) [18-20], which means that the increase in temperature tends to keep the solar cell in open circuit situation and therefore increases the series resistance.

Conclusion

We have just studied the effect of temperature on the series resistance of a silicon solar cell under polychromatic illumination and in static regime. The determination of the minority charge carriers density from the equation of continuity made it possible to obtain the photocurrent and the Photovoltage. The Photocurrent - Photovoltage characteristic showed a decrease in photocoupling and photovoltage when the temperature increases. The series resistance is determined from the Photocurrent - Photovoltage characteristic knowing the recombination velocity of the minority charge carriers at the junction limiting the open circuit Sfoc. Thus, the study showed a decrease in Sfoc and an increase in series resistance when the temperature increases.

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